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## Polariton effect in a photonic crystal slab

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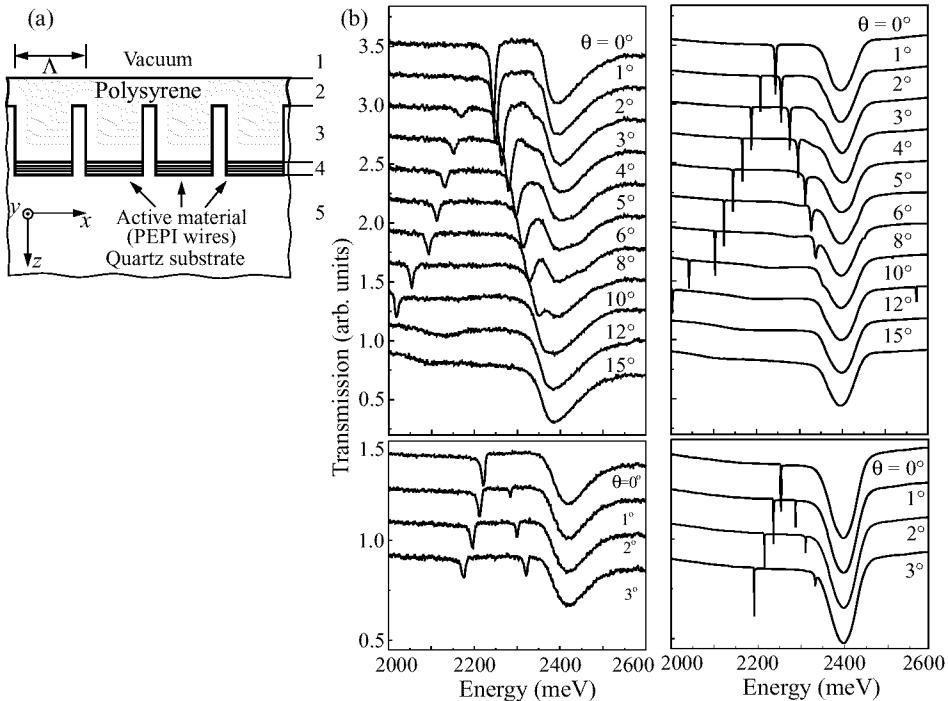
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**Abstract.** We have investigated theoretically and experimentally the transmission of light through a photonic crystal of finite thickness, a distributed feed-back (DFB) microcavity with one dimensionally (1D) arranged semiconducting wires. To describe this system theoretically we have developed a numerical method, based on scattering matrix formalism, which takes into account the polaritonic effect via the exciton poles in dielectric susceptibility of the semiconducting wires. Theoretical results reproduce and explain the characteristic measured features of the transmission spectra such as anticrossing behavior of transmission dips in vicinity of the excitonic resonance and strong polarization dependence of their position and depth.

The optical properties of photonic crystals have been the subject of intensive studies during the past decade. As the next phase, it is interesting and meaningful to introduce an optically active semiconducting material into such systems to provide a strong interaction of excitons with Bloch-like photonic modes. This interaction can considerably change the optical response of the whole system, which opens a way for designing new high-performance optical devices such as ultralow-threshold lasers. Among the most well studied realizations of these periodic semiconductor structures we should point out so called Bragg superlattices, i.e., the systems of multiple quantum wells [1, 2, 3] or quantum wires [4] coupled via resonant photons.

In the present work we study the optical properties of another realization of such a system, namely, a distributed feedback (DFB) microcavity [5]. In this DFB microcavity a rectangular mesoscopic wires of self-organized PbI-based layered organic-inorganic semiconductor were arranged periodically on a quartz substrate. Owing to the effect of dielectric enhancement, the excitons in this material have large binding energies and oscillator strengths [6], which leads to a strong polaritonic effect.

The structure of the DFB microcavity is schematically shown in Fig. 1(a). The cavity consists of quartz grating substrate, semiconducting (active) layer, and polystyrene over-coating film. The grating was fabricated on a quartz substrate by means of the electron-beam lithography and dry etching techniques. Typical grating pitch ( $\Lambda$ ), depth ( $h$ ), line-to-space ratio, and area are, respectively, 0.7, 0.4  $\mu\text{m}$ , 1:4, and  $1.5 \times 1.5 \text{ mm}$ . The thickness of active and overcoating layers are estimated in our work as 18 nm and 50 nm, respectively. The active material used is  $(\text{C}_6\text{H}_5\text{C}_2\text{H}_4\text{NH}_3)_2\text{PbI}_4$ , [bis-(phenethylammonium) tetraiodoplumbate] (PEPI) which is one of the  $\text{PbI}_4$ -based layered perovskite-type semiconductors consisting of self-organized multiple-quantum-well structure with  $[\text{PbI}_6]^{4-}$  layers as wells and organic alkylammonium layers as barriers. Excitons in the quantum wells are strongly enhanced due to a large difference in dielectric constants between the wells ( $\epsilon_{\text{well}} = 6.41$ ), and the barriers ( $\epsilon_{\text{bar}} = 2.34$ ). The exciton binding energy, oscillator



**Fig. 1.** (a) Schematic structure of DFB microcavity. (b) Measured (left) and calculated (right) transmission spectra of DFB microcavity for different incidence angles  $\theta$ , in *S*- (top) and *P*-polarizations (bottom).

strength, and longitudinal-transverse (LT) splitting in PEPI are extremely large: 220 meV, 0.5 per formula unit, and 50 meV, respectively. Six gratings were made on a quartz substrate with grating pitch  $\Lambda_x$  ranging from 0.62 to 0.72  $\mu\text{m}$  every 20 nm, so that it was possible to compare their transmission spectra under the same conditions. Transmitted intensity of a light through the sample was measured in Ref. [4] as a function of the photon energy for different gratings and for different angles of incidence.

The optics of infinite polaritonic crystal with full allowance for nonlocal effects has been recently studied in Ref. [7]. It turns out, however, that the main characteristic features of the optical response of DFB microcavities can be satisfactorily modeled within a local polariton response theory, because the wavelength of light is much larger than all characteristic exciton lengths. Much more important is to take into consideration the finite thickness of the polaritonic crystal, and to analyze the optical response of the system for arbitrary polarization and angle of incidence.

To describe the system theoretically we have built up a numerical scheme, which utilizes and develops approaches of Refs. [8] and [9]. The scheme was proved to work for arbitrary number of layers, arbitrary angle of incidence and polarization state of incoming light, the case of 2D patterning of DFB microcavity layers can be included as well. Moreover, we have focused our interest on polaritonic effects in transmission properties of periodic multilayer structure, which is principally new.

The theoretical procedure [10] can be divided into three logical steps.

(i) We split the whole structure into layers, either homogeneous or periodical in  $xy$ -plane, to define tensors of the dielectric susceptibilities in each layer. The model structure, shown on Fig. 1(a) consists of five layers with layers 3 and 4 periodically patterned.

(ii) We find a general solution of the Maxwell's equations in each layer. To do so, we use the plane waves decomposition of the electric and magnetic fields expanding it into Fourier series in  $x$ -direction (the axis of periodicity). The local piecewise-constant dielectric susceptibility is also Fourier transformed, and the most important point here is its frequency dependence which appears due to the inclusion of the exciton pole in semiconductor. Then the Maxwell's equation is converted into infinite-matrix eigenproblem for  $x$ ,  $y$ -amplitudes of the electric field serving as an eigenvector and the  $z$ -projection of the wavevector as an eigenvalue. In numerical calculations the infinite matrix problem is truncated in a way to hold all important Fourier harmonics (Bragg reflections). The general solution becomes a superposition of these basic eigenvectors corresponding to along- and counter-propagating partial waves.

(iii) Using the Maxwell's boundary conditions we generate a transfer matrix, which connects the amplitudes of partial waves in different layers throughout the whole system, and then apply the scattering matrix formalism [9]. It's essential to note that the scattering matrix method allows us to avoid numerical instability caused by appearance of evanescent waves. Finally we calculate the coefficients of reflection, transmission, and absorption of the whole system.

The experimentally measured and calculated within our theoretical model transmission spectra of DFB structure with  $\Lambda = 0.72 \mu\text{m}$  are shown in Fig. 1(b) (left and right panels, respectively), for  $S$ - and  $P$ -polarization (top and bottom, respectively) and different angle of incidence  $\theta$ . A broad absorption band near 2.4 eV which is clearly seen in all plots of Fig. 1(b) corresponds to the lowest ( $1S$ ) exciton transition in the PEPI material. Sharp dips to the left of the exciton-like mode are the DFB cavity modes. The lower (upper) line originates from the top of the fourth (bottom of the fifth) photonic band. In case of  $S$ -polarization the eigenmode of the fourth band appears to be anti-symmetric in the center of the first Brillouin zone (BZ), and the eigenmode of the fifth band appears to be symmetric. Vice versa, in case of  $P$ -polarization the eigenmode of the fourth band is symmetric in the center of the first BZ, and the eigenmode of the fifth band is anti-symmetric. Thus, for  $\theta = 0$ , which corresponds to the center of the first BZ, only the upper line is seen for  $S$ -polarization, and only the lower one is seen for  $P$ -polarization, because anti-symmetric modes do not interact with symmetric field of incoming light at normal incidence. When moving away from the center of Brillouin zone ( $\theta$  increases), both the symmetric and anti-symmetric modes become visible and the upper lines show a strong polariton mixing with excitonic mode.

In conclusion, we have investigated the optical properties of 1D patterned distributed feedback microcavities with strong exciton-photon coupling. We have developed a theoretical model of calculation of the optical response of such a layered system for arbitrary geometry of the incident beam. This model quantitatively reproduces the experimental behaviour of the DFB microresonator transmission.

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